

# Quark Delocalization, Color Screening, and Nuclear Intermediate Range Attraction

Fan Wang,<sup>1)</sup> Guang-han Wu,<sup>2)</sup>,  
Li-jian Teng,<sup>2)</sup> and T. Goldman,<sup>3)</sup>

<sup>1)</sup> Center for Theoretical Physics, Nanjing University, Nanjing, China, 210008 and  
CCAST (World Laboratory)

<sup>2)</sup> Institute of Nuclear Science and Technology, Sichuan University, Cheng-du,  
China, 610064

<sup>3)</sup> Theoretical Division, Los Alamos National Laboratory, NM 87545, USA

## Abstract

We consider the effect of including quark delocalization and color screening, in the nonrelativistic quark cluster model, on baryon-baryon potentials and phase shifts.

We find that the inclusion of these additional effects allows a good qualitative description of both.

## I. Introduction

Up to now, all quark model calculations (including potential, bag, and soliton models) of the nuclear force have found difficulty in obtaining the observed intermediate range attraction.<sup>[1]</sup> It is not even technically easy for meson exchange models<sup>[2]</sup> to do so. Therefore, one should consider the possibility that all of these models have omitted important physical effects.

In molecular physics, experience shows that electron delocalization is an important effect contributing to the formation of chemical bonds. Is there a similar effect for the nuclear bond due to quark delocalization? (This effect has also been called quark percolation in view of the fact that quarks are confined in color singlet hadrons.)

As in molecular physics, there are also other forces at work. There, multiphoton exchange produces (van der Waals') interactions between neutral atoms. But there is no evidence for (color van der Waals') multigluon exchange forces between color singlet hadrons. So, although inside a hadron, quarks experience a confining interaction, between two colorless hadrons, the confinement interaction must certainly be modified. Lattice gauge calculations have indeed shown qualitatively that there is a color screening effect due to  $q\bar{q}$  excitation<sup>[3]</sup>. How important color screening is to the nuclear interaction remains an open question.

We have made a (nonrelativistic) QCD model calculation to study whether a nuclear intermediate range attraction arises when we take into account the possibility of both quark delocalization and color screening. The result we find is that quark delocalization and color screening actually do seem to give rise to an effect very similar to the nuclear intermediate range attraction. It seems that quark delocalization and color screening may play an effective role similar to meson exchange.

## II. The Quark Delocalization and Color Screening Model

We take a nonrelativistic quark cluster model to generate our QCD model for the baryon-baryon interaction. The new ingredients are quark delocalization and color screening. For individual baryons, our model is the same as the usual one<sup>[4]</sup>. That is

we have the Hamiltonian

$$H = \sum_i (m_i + \frac{P_i^2}{2m_i}) - T_c + \sum_{i < j} V_{ij} \quad (1)$$

$$V_{ij} = V_{ij}^C + V_{ij}^G \quad (2a)$$

$$V_{ij}^C = -\vec{\lambda}_i \cdot \vec{\lambda}_j a r^2 \quad (2b)$$

$$V_{ij}^G = \alpha_S \frac{\vec{\lambda}_i \cdot \vec{\lambda}_j}{4} \left[ \frac{1}{r} - \frac{\pi}{2} \delta(\vec{r}) \left( \frac{1}{m_i} + \frac{1}{m_j} + \frac{4}{3m_i m_j} \vec{\sigma}_i \cdot \vec{\sigma}_j \right) \right] \quad (2c)$$

where  $\vec{r} = \vec{r}_i - \vec{r}_j$  and  $T_c \equiv$  center of mass kinetic energy. Here we keep only the effective one gluon exchange form of the color Coulomb and hyperfine terms and also neglect a possible constant part of the confining interaction. We do so because we are interested in the qualitative features of this model and wish to keep the number of parameters to a minimum. It should be noted, however, that our form for  $V_{ij}$  is consistent with all charmonium and Upsilon bound state spectra.<sup>[5]</sup>

The single quark orbital wave function is chosen to be a Gaussian function

$$\psi(\vec{r}_i) = \left(\frac{1}{\pi b^2}\right)^{3/4} \exp\left\{-\frac{1}{2b^2}(\vec{r}_i - \vec{R})^2\right\} \quad (3)$$

where  $\vec{R}$  is the reference center (mean location of the baryon). The parameters are determined as follows. We choose the constituent quark mass to be exactly 1/3 of the nucleon mass, i.e.  $m = 313MeV$ , so that the binding energy of the nucleon is exactly zero. We also require the model to produce the correct  $N - \Delta$  mass difference and that the nucleon size satisfies the stability condition, i.e.  $\delta M_N / \delta b = 0$ . The fitted model parameters are:

$$m = 313MeV, \quad b = 0.603fm, \quad \alpha_S = 1.54, \quad a = 25.13MeV/fm^2 \quad (4)$$

These are similar to the parameters chosen in Ref. [4].

For the two baryon system, we take a two “center” cluster model approximation, i.e., we have the left (right) single quark orbital wavefunction (w. f. )

$$\phi_L(\vec{r}_i) = \left(\frac{1}{\pi b^2}\right)^{3/4} \exp\left\{-\frac{1}{2b^2}(\vec{r}_i + \vec{R}/2)^2\right\} \quad (5a)$$

$$\phi_R(\vec{r}_i) = (\frac{1}{\pi b^2})^{3/4} \exp\{-\frac{1}{2b^2}(\vec{r}_j - \vec{R}/2)^2\} \quad (5b)$$

Now  $\vec{R}$  is the distance between the two clusters.

The variational trial w.f. of the two baryon system is an antisymmetric six quark product state

$$\Psi(B_1 B_2) = \mathcal{A}\{[\psi_L(1)\psi_L(2)\psi_L(3)]_{B_1}[\psi_R(4)\psi_R(5)\psi_R(6)]_{B_2}\}_{ST} \quad (6)$$

$\mathcal{A}$  is the antisymmetrization operator,  $[ ]_B$  means the spin, isospin, and color of the three quarks are coupled to the quantum numbers of a baryon,  $\{ \}_{ST}$  means the spin, isospin and color of the two baryons are coupled to the particular color singlet channel of spin  $S$  and isospin  $T$ .

One of our new ingredients, quark delocalization, is put in through the trial single quark w. f.  $\psi$

$$\psi_L = \phi_L + \epsilon\phi_R, \quad \psi_R = \phi_R + \epsilon\phi_L \quad (7)$$

where  $\epsilon = \epsilon(\vec{R})$  (see below) is a variational parameter determined by a variational calculation, after the manner suggested in Ref. [6] in a relativistic quark picture of nuclear structure. We explicitly examine here only the  $\epsilon > 0$  region. Numerical results for negative  $\epsilon$  show increased energy for the state. This confirms expectations based on viewing this case as including  $p$ -wave contributions of necessarily higher energy, or from the point of view of two-state mixing (producing symmetric and antisymmetric states in the  $\epsilon = \pm 1$  limit).

The other new ingredient, color screening, is put in through the modification of the confinement interaction between two color singlet baryons

$$V_{ij}^{SC} = -\vec{\lambda}_i \cdot \vec{\lambda}_j a r^2 e^{-\mu r^2} \quad (8)$$

When we calculate the six quark confinement interaction matrix elements, we separate them into internal and inter-cluster parts: for the latter we use the screening confinement interaction  $V_{ij}^{SC}$ . Note that  $\mu$  is a parameter which will be fixed by data. However, since we have alluded to screening (found in lattice calculations) due to  $q\bar{q}$  production, and the scale for that is set by the pion mass, we expect  $\mu \sim m_\pi^2$  to result.

We do two kinds of calculations. First we calculate the diagonal matrix element

$$\frac{\langle \Psi_{B_1 B_2}(\vec{R}) | H | \Psi_{B_1 B_2}(\vec{R}) \rangle}{\langle \Psi_{B_1 B_2}(\vec{R}) | \Psi_{B_1 B_2}(\vec{R}) \rangle} - \frac{\langle \Psi_{B_1 B_2} | H | \Psi_{B_1 B_2} \rangle}{\langle \Psi_{B_1 B_2} | \Psi_{B_1 B_2} \rangle} \bigg|_{\vec{R}=\infty} \quad (9)$$

to get the adiabatic approximation to the baryon-baryon interaction. For fixed  $\mu$  at each separation  $\vec{R}$ , we vary the parameter  $\epsilon(\vec{R})$  to get the minimum. (We then vary  $\mu$ , repeating the calculation until we get a best fit for the  $NN \ ^1S_0$  phase shift, i. e. minimum  $\chi^2$  per degree of freedom; see below). We take this as the approximation of our model baryon-baryon interaction.

Second, we do a dynamical calculation to get the phase shift of baryon-baryon scattering. When we do this calculation, we have to calculate the off-diagonal kernel in addition to the diagonal one:

$$\langle \Psi_{B_1 B_2}(\vec{R}) | H | \Psi_{B_1 B_2}(\vec{R}') \rangle \quad (10)$$

For  $\Psi(\vec{R})$  we use the parameter  $\epsilon = \epsilon(\vec{R})$  and for  $\Psi(\vec{R}')$  we use  $\epsilon = \epsilon(\vec{R}')$ . Finally we use the Canto-Brink<sup>[7]</sup> (CB) variational method to calculate the phase shift and vary  $\mu$  to get a best fit to  $NN \ ^1S_0$  phase shift. The CB method is equivalent to the more popular resonating group method (RGM).<sup>[8]</sup>

### III. Results and Discussion

We have calculated the effective baryon-baryon interaction and the phase shifts for  $NN \ (S, T) = (1, 0), (0, 1)$  and  $\Delta\Delta \ (S, T) = (3, 0)$  channels. The results are shown in Figs. 1-2. The experimental phase shifts are taken from Table IV of Ref. [9]. The optimum color screening constant is  $\mu = 0.46 \text{ fm}^{-2}$ , consistent with our expectations. The results are not very sensitive to  $\mu$  within the range 0.4 to 0.5  $\text{fm}^{-2}$ , and an intermediate attraction persists over an even wider range of values. (It would be interesting to compare this with meson exchange results over a range of pion mass values.) The fitted quark delocalization parameters  $\epsilon$  are given in Table 1.

It is well known that the pure quark cluster with gluon exchange model can only give rise to a  $N - N$  repulsive core. Figs. 1 and 2 however, show that quark

delocalization and color screening working together can produce a good description of the  $N - N$  interaction: it has both the repulsive core *and* an intermediate range attraction. Further, the  $NN \ ^3S_1$  channel attraction is stronger than  $^1S_0$  channel. Qualitatively the result fits the  $^1S_0$  channel phase shifts; it also gives a qualitative fit for the  $^1D_2$  phase shifts. The fit to the  $^3S_1$  phase shifts is not as good as  $^1S_0$ , and  $^1D_2$ . This is not unreasonable, because we have not yet included the tensor coupling.

This model also automatically gives a reasonable amount of delocalization. When the two nucleons are close together, the delocalization is large;  $\epsilon(R = 0.375 fm) \sim 1$ , which means that at short distances, the six quarks prefer to merge into a six quark state instead of two nucleons.<sup>[10,11]</sup> However, when the two nucleons separate to a distance comparable to the average distance between nucleons in a nucleus, the delocalization is small:  $\epsilon(R = 1.5 fm) \sim 0.1$ , which means the six quarks prefer to be confined in two individual nucleons.<sup>[6]</sup>

It is worth mentioning here that the quark delocalization and color screening effects must both be included; dropping either one causes the  $NN$  intermediate attraction to disappear. However the  $NN$  intermediate range attraction mainly comes from the kinetic energy reduction due to quark delocalization. It is only somewhat concealed by the screened confining interaction. If we drop the color screening, however, the confinement interaction contribution related to the quark delocalization will cancel the attraction coming from the kinetic energy reduction related to the same quark delocalization.

It seems likely that the effective attraction due to quark kinetic energy reduction, which in turn comes from quark delocalization, is quite general for all quark systems. To show this, we have also calculated the adiabatic interaction potential and phase shifts of the  $\Delta\Delta \ (S, T, \ell = 3, 0, 0)$  channel. We find that it is indeed an “inevitable” dibaryon state; our new nonrelativistic quark cluster model also gives a strong intermediate attraction, which supports the original LAMP calculation.<sup>[12]</sup> The reason for a stronger  $\Delta\Delta$  attraction than that of  $NN$  channels is due to a reduction in the cancellation of the attraction due to quark delocalization by the screening confinement interaction in the  $\Delta\Delta \ (S, T, \ell = 3, 0, 0)$  channel.

Note that there is no color van der Waals' force problem for this model because we have taken color screening into account; any such forces become gaussianly suppressed. Whether this model also gives a bound "H"-state particle is an interesting question; a three channel coupling calculation is in progress. At the same time, we will check if this model can give a reasonable deuteron bound state, which would imply that the agreement with the phase shifts extends to very low energy.

Several points remain to be studied:

1. Due to the quark delocalization, the center of mass wave function of this six quark system can not be separated in as clear cut a way as in the usual cluster model. To develop a method to separate the center of mass wave function explicitly would be highly desirable.
2. We have given an intuitive argument for quark delocalization and color screening. A better basis in QCD is needed.
3. This model seems to imitate meson exchange to some extent, but the detailed relation between quark delocalization and meson exchange is not yet clear.
4. The model qualitatively fits both hadron spectroscopy and the  $NN$  interaction, and quark delocalization seems to be a general feature for all quark systems. Therefore it would be interesting to confront this model with possible dibaryon resonances.

We are happy to thank Jerry Stephenson, Kim Maltman, Karl Holinde and Joe Carlson for valuable discussions. We also thank LAMPF, TRIUMF, and the Institute for Nuclear Theory (Seattle), where parts of this work were conceived, for their hospitality.

This work was supported in part by the National Science Foundation of China and the US DOE.

## References

1. Y. Fujiwara and K. T. Hecht, *Nucl. Phys.* **A444**, 541 (1985) and references therein.
2. R. Machleidt, K. Holinde and Ch. Elster, *Phys. Rep.* **149**, 1 (1987).
3. B. Svetitsky in “*Nuclear Chromodynamics*”, ed. by S. Brodsky and E. Moniz (World Scientific, Singapore, 1986) pp.80-81.
4. N. Isgur and G. Karl, *Phys. Rev. D* **20**, 1191 (1979).
5. W. Kwong, J. L. Rosner and C. Quigg, *Ann. Rev. Nucl. Part. Sci.* **37**, 325 (1987).
6. T. Goldman, K. Maltman, G. J. Stephenson, Jr. and K. E. Schmidt, *Nucl. Phys.* **A481**, 621 (1988).
7. L. F. Canto and D. M. Brink, *Nucl. Phys.* **A279**, 85 (1977).
8. G. H. Wu and D. L. Yang, *Scientia Sinica, Suppl. A*, 1112 (1982).
9. R. A. Arndt, *et al.*, *Phys. Rev. D* **28**, 97 (1983).
10. G. E. Brown and M. Rho, *Phys. Lett.* **82B**, 177 (1979). For a full discussion, see Y. He, F. Wang, and C. W. Wong, *Nucl. Phys.* **A448**, 652 (1986).
11. E. M. Henley, L. S. Kisslinger, and G. A. Miller, *Phys. Rev. C* **28**, 1277 (1983).
12. T. Goldman, K. Maltman, G. J. Stephenson, Jr. , K. E. Schmidt, and F. Wang *Phys. Rev. C* **39**, 1889 (1989).



Table 1. Quark Delocalization Parameters  $\epsilon(\vec{R})$

R(fm)	0.375	0.750	1.125	1.500	1.875	2.250	2.625	3.000
$NN\ ^1S_0$	0.999	0.510	0.166	0.123	0.077	0.038	0.015	0.005
$NN\ ^3S_1$	0.999	0.994	0.229	0.155	0.093	0.045	0.017	0.005
$\Delta\Delta\ ^7S_3$	0.999	0.999	0.999	0.999	0.999	0.999	0.208	0.055

## Figure Captions

Figure 1. Baryon-baryon potentials as a function of separation in the quark cluster model with quark delocalization and color screening; a) two  $NN$  channels, b) a  $\Delta\Delta$  channel, c) detail of a) in region of minimum.

Figure 2. Nucleon-nucleon phase shifts as a function of beam kinetic energy in the quark cluster model with quark delocalization and color screening, and the corresponding data from Table IV of Ref. [9]. The parameters have been chosen to best fit the  $^1S_0$  channel. Note that tensor forces, which affect only the  $^3S_1$  channel here, have not been included.